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Groundwater vulnerability of a shallow low-lying coastal aquifer in southern Finland under climate change

Samrit Luoma

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Groundwater vulnerability of a shallow low-lying coastal aquifer in southern Finland under climate change

by

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ACADEMIC DISSERTATION

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Front cover: The shallow, unconfined, low-lying coastal aquifer in Hanko, southern Finland.
Photo: Samrit Luoma, GTK.

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ABSTRACT

This thesis clarifies the potential impacts of climate change and sea-level rise under future climate scenarios on groundwater recharge and surface leakage, and consequently on the groundwater vulnerability of a shallow, unconfined, low-lying coastal sedimentary aquifer in southern Finland. The study utilised multiple approaches, including field investigations, well monitoring, three-dimensional (3D) geological modelling, 3D groundwater flow modelling, multivariate statistical approaches (principal component analysis (PCA) and hierarchical cluster analysis (HCA)), the stable isotopes ^{2}H and ^{18}O, conventional hydrogeochemistry and groundwater intrinsic vulnerability assessment methods. The UZF1 model was coupled with the 3D groundwater MODFLOW model to simulate flow from the unsaturated zone through the aquifer. The well-calibrated groundwater flow model was used to simulate and predict the potential impacts of climate change on groundwater recharge under future climate and sea-level rise scenarios. The results indicate changes in the groundwater recharge patterns during the years 2071–2100, with recharge occurring earlier in winter and early spring. Because the aquifer is located in a cold snow-dominated region, the seasonal impacts of climate change on groundwater recharge were more significant, with land surface overflow resulting in flooding during the winter and early spring and drought during the summer. Rising sea levels would cause some parts of the aquifer to be submerged under the sea, compromising groundwater quality due to the intrusion of seawater. This, together with increased groundwater recharge, would raise the groundwater level and consequently contribute to more surface leakage.

The groundwater geochemistry of the coastal aquifer in Hanko is very similar to that of inland shallow aquifers generally in Finland, where the groundwater is mainly of the Ca–HCO_3 type, with low dissolved element concentrations, low pH and alkalinity, and low Ca and Mg concentrations due to rapid percolation or the short residence time. The stable isotopes ^{2}H and ^{18}O clearly suggest that the Hanko aquifer recharges directly from meteoric water (snowmelt and rainfall), with minor or insignificant contributions from the Baltic Sea and surface water. However, the geochemistry of the groundwater suggests sulphate reduction in the mixed zone between freshwater and seawater, indicating that local seawater intrusion may temporarily take place, although the contribution of seawater was found to be very low. Further inland, the influence of surface water could be observed from higher levels of $KMnO_4$ consumption in wells near the lake above the aquifer. The findings also demonstrated that the use of stable isotopes ^{2}H and ^{18}O alone to identify seawater–aquifer interaction is not sufficient to determine the rate of water exchange. The high temporal variation in groundwater chemistry directly corresponded to groundwater recharge. With an increase in groundwater recharge, $KMnO_4$ consumption, EC, alkalinity and Ca concentrations also increased in most wells, while Fe, Al, Mn and SO_4 were occasionally increased during the spring after snowmelt under specific geological conditions. Based on the future climate scenarios, precipitation in the Hanko area is expected to increase and the Baltic Sea level to rise. This could cause increased recharge of the aquifer from surface water, but also some seawater intrusion due to the sea-level rise and storm surges, as well as increased groundwater abstraction. An increase in the concentrations of some dissolved elements and changes in groundwater geochemistry along the coastline can be expected in the future. Thus, in coastal aquifers with low hydraulic gradients, the hydrogeochemistry should be used to confirm the intrusion of seawater. The PCA and HCA multivariate statistical approaches are useful tools to extract the main components that are able to identify the vulnerable areas of the aquifer impacted by natural or human activities, either on regional or site-specific scales. The integration of PCA and HCA with conventional classification of groundwater types, as well as with the hydrogeochemical data, provided an understanding of the complex groundwater flow systems, supporting aquifer vulnerability assessment and groundwater management in the future.

The degree of groundwater vulnerability in the Hanko aquifer has been greatly impacted by seasonal variations in groundwater recharge during the year, and will also vary depending on climate change variability in the long term. The potential for high groundwater vulnerability to contamination from sources on the ground surface occurs during the period with a high groundwater recharge rate after snowmelt, while high vulnerability to seawater intrusion could occur when there is a low groundwater recharge rate in the dry season. This thesis study highlighted the importance of the integration of groundwater vulnerability assessment methods for shallow, unconfined, low-lying coastal aquifers from a comparison of three intrinsic vulnerability mapping methods: the AVI, a modified version of SINTACS and the GALDIT method. The modified SINTACS could be used as a guideline for groundwater vulnerability assessment of glacial and deglacial deposits in inland aquifers, and in combination with GALDIT, it could provide a useful tool for assessing groundwater vulnerability to both contamination from sources on the ground surface and to seawater intrusion for shallow, unconfined, low-lying coastal aquifers under future climate change.

Keywords: aquifers, ground water, brackish-water environment, coastal environment, climate change, recharge, vulnerability, three-dimensional models, geochemistry, Hanko, Finland

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following three papers, which are referred to in the text by their Roman numerals.

I Luoma, S. & Okkonen, J. 2014. Impacts of Future Climate Change and Baltic Sea Level Rise on Groundwater Recharge, Groundwater Levels, and Surface Leakage in the Hanko Aquifer in Southern Finland. Water 2014, 6(12), 3671-3700, doi:10.3390/w6123671

II Luoma, S., Okkonen, J., Korkka-Niemi, K., Hendriksson, N. & Backman, B. 2015. Confronting the vicinity of the surface water and sea shore in a shallow glaciogenic aquifer in southern Finland. Hydrol. Earth Syst. Sci. 19, 1353–1370, doi:10.5194/hess-19-1353-2015

III Luoma, S., Okkonen, J. & Korkka-Niemi, K. 2016. Comparison of the AVI, modified SINTACS and GALDIT vulnerability methods under future climate-change scenarios for a shallow low-lying coastal aquifer in southern Finland. Hydrogeology J., doi:10.1007/s10040-016-1471-2

THE AUTHOR'S CONTRIBUTION TO PUBLICATIONS:

I. Designed the study with the co-author. Conducted the data analysis, model development and simulation work. Wrote the paper and prepared the figures, which were commented on by the co-author. The co-author introduced the UZF1 method to couple with MODFLOW for groundwater flow simulation as well as supervised in the simulation work. The co-author also provided the snow-water equivalent input data for the simulation in this study.

II. Designed the study with the co-authors. Conducted the fieldwork, water sampling, data analysis and interpretation. Wrote the paper and prepared the figures, which were commented on by the co-authors. B. Backman and N. Hendriksson provided guidance in field measurements and water sampling. N. Hendriksson provided the results of the stable isotope analysis and wrote part of the stable isotope analysis (3.3). K. Korkka-Niemi and J. Okkonen supervised in the multivariate statistical analysis (PCA and HCA) and provided guidance in the structure of the paper.

III. Designed the study with the co-authors. Conducted the vulnerability mapping, data analysis and interpretation. Wrote the paper and prepared the figures, which were commented on by the co-authors. In this paper, the author proposed the methods to be used for the assessment of the intrinsic vulnerability of groundwater, which consisted of GALDIT method for the intrinsic vulnerability assessment of seawater intrusion into the coastal aquifer, and a modified version of SINTACS method to make the vulnerability index more suitable for glacial aquifer deposits and deglaciation depositional environments, which are important shallow aquifers in Finland.

1 INTRODUCTION

1.1 Groundwater and climate change

Shallow permeable aquifers located in low-lying coastal areas are vulnerable not only to contamination from sources that are located on the ground surface, but also to seawater intrusion and/or flooding of coastal areas either due to sea-level rise or storm surges (e.g. Luoma et al. 2013, Oude Essink 1999, 2001, Barlow 2003, Pulido-Leboeuf 2004, Oude Essink et al. 2010, Rasmussen et al. 2013, Ferguson & Gleeson 2012, Ataie-Ashtiani et al. 2013). These events will presumably be accelerated by the changing climate, including changes in precipitation, temperature and groundwater recharge, as well as sea-level rise and an increasing frequency of storm surges (IPCC 2000, 2007, Nicholls et al. 2007). Besides these, the increasing demand for water by the population and industry, as well as changing land-use practices as a result of human activities such as exceeding the water intake, gravel excavation pits, car parking and groundwater contamination risk areas, can expose shallow aquifers to contamination. Ferguson and Gleeson (2012) reported that due to groundwater abstraction and the low hydraulic gradient, saltwater intrusion into coastal aquifers will become more widespread and significant than assumed based on the impact of sea-level rise.

Groundwater recharge is an important process in maintaining the groundwater levels and the sustainability of groundwater resources. Future climate change will influence hydrological systems, groundwater recharge and groundwater resources. The increasing trend for global warming is predicted to continue in the future and is expected to have greater impacts on hydrological systems, resulting in more vulnerable water resources (IPCC 2000, 2007).

In permeable, unconfined sedimentary aquifers located in low-lying coastal areas, changes in sea- level and potential future sea-level rise may affect groundwater quantity and quality due to saltwater intrusion (Oude Essink 1999, 2001, Oude Essink et al. 2010, Rasmussen et al. 2013). Climate change could potentially affect not only groundwater, but also surface water. Surface leakage represents groundwater that leaves an aquifer in the form of discharged water to the land surface whenever the altitude of the groundwater table exceeds the land surface (Niswonger et al. 2006). If surface leakage were to increase in the future, this would have direct implications, e.g., for land-use planning. Increased surface leakage could also cause flooding and contamination of wells (Korkka-Niemi 2001). In addition, seawater intrusion can increase the salinity of coastal freshwater aquifers. For sustainable groundwater resource management and land-use planning, it is important to understand the hydrogeological processes and the interactions between groundwater and surface water, and the factors affecting groundwater quality. Therefore, there is an urgent need to assess the potential impact of future climate change on low-lying aquifers that are vulnerable to changes in groundwater conditions.

Numerical simulation models provide an effective way to estimate the quantity and quality of groundwater and surface water interaction and to quantify the impact of climate change on groundwater resources. A number of recent studies have assessed the impact of climate change on groundwater using groundwater flow modelling as an assessment tool, and have found that recharge estimation is one of the most challenging parts of the modelling (Scibek & Allen 2006, Scibek et al. 2007, Jyrkama & Sykes 2007, Okkonen 2011, Jackson et al. 2011, Ali et al. 2012, Assefa & Woodbury 2013). One alternative approach could be solving Richards' equation in three-dimensions (3D) to simulate the flow from the unsaturated zone down to the groundwater table. A few numerical models are available that are able to solve Richards' equation in 3D, for example HydroGeoSphere (HGS) (Therrien et al. 2012), OpenGeoSys (Kolditz et al. 2012), ParFlow (Maxwell & Miller 2005, Kollet & Maxwell 2008) and FLUSH (Warsta 2011). However, solving Richards' equation in 3D, especially in a regional-scale model, can be computationally demanding (Harter & Morel-Seytoux 2013), and hence more robust approaches could be used in practical applications such as one-dimensional (1D) unsaturated-zone flow UZF1 coupled with MODFLOW (Niswonger et al. 2006, Bailey et al. 2013). UZF1 is implicitly coupled to MODFLOW by iteratively balancing the dependence of groundwater recharge and discharge on the groundwater head. In addition, it has been pointed out that on a regional scale with large space and time discretization, the solution of Richards' equation such as in HGS may not be more inaccurate than the simplified process of coupling UZF1 with MODFLOW (Harter & Morel-Seytoux 2013).

A number of fully coupled approaches have also been developed and used to simulate sea-aquifer interactions in order to determine the density variation in groundwater and sea-aquifer interface. For example, coupled MODFLOW and MT3DMS have been used to simulate the variable-density groundwater flow and solute transport in the SEAWAT computer program (Langevin & Guo 2006). HGS has been used to simulate the effects of tides and storm surges on a coastal aquifer (Yang et al. 2013). Another study summarized the processes, measurement, prediction and management of seawater intrusion in a coastal aquifer including a number of computer codes that are capable of simulating seawater intrusion into the coastal aquifer (Werner et al. 2013). The fully coupled sea-aquifer model in conjunction with a 3D Richard's equation would probably be the most accurate tool to estimate the interaction and the interface between seawater and groundwater. However, the density of the Baltic Sea is relatively low, on average 1.005 kg m^{-3}, compared with that of normal oceanic water (average 1.025 kg m^{-3}) (Leppäranta & Myrberg 2009). In the Gulf of Finland, the density of seawater varies from 1.001 to 1.006 kg m^{-3} (average 1.003 kg m^{-3}) and salinity from 3.0‰ to 10.23‰ (average 6.6‰) (Feistel et al. 2012). The salinity value varies with depth, from 3.0‰ to 5.5‰ in shallow water (Fagerlund 2008) up to 10.23‰ at a maximum water sampling depth of 80 m (Fagerlund 2008). These values appear to remain stable, as they are similar to those determined for water samples taken more than 30 years ago in this area (Millero & Kremling 1976). In future climate change scenarios, salinity in the central Baltic Sea is predicted to decrease by about 2.0‰–2.5‰ (Neumann et al. 2012), with a decrease of 8%–50% from the present for the whole Baltic Sea region (Meier et al. 2006), due to the predicted increase in freshwater inflow into the Baltic Sea. Moreover, the annual seawater level varies between 2.0 and -1.3 m along the Finnish coast (FMI 2014), and no tides have been reported in the Baltic Sea (Håkanson 2003). So far there is no predicted data on density changes in the Baltic Sea under the climate change scenarios. The Baltic Sea level rise and fluctuation estimated for various climate change scenarios can be used in the first instance to estimate the impacts of Baltic Sea level fluctuation and its impacts, together with those of changes in climate variables, on groundwater and interactions between the Baltic Sea and aquifers connected to it.

Under the changing climate, a potential increase in precipitation in the winter, spring and autumn and increased evapotranspiration in the summer owing to rising temperatures is expected (Okkonen & Kløve 2011, Okkonen 2011). Seasonal variations in groundwater quality and the direct correlation between its quality and the amount of precipitation have been reported in many unconfined shallow aquifers in Finland (e.g. Backman et al. 1999, Korkka-Niemi 2001, Okkonen 2011). However, there is still no clear understanding of the interactions between surface water and groundwater or the impacts of brackish water intrusion on shallow, low-lying coastal aquifers. Major ion chemistry, as well as the stable isotopic composition of oxygen-18 (^{18}O) and hydrogen-2 (^{2}H or deuterium), could be used to assess these interactions, as earlier reported by Allen (2004), Harbison (2007), Kortelainen (2007) and Mongelli (2013), among others.

1.2 Groundwater vulnerability

The intrinsic vulnerability of an aquifer is the relative degree of natural protection of an aquifer from contamination by anthropogenic sources at the land surface. It is defined as a function of the hydrogeological characteristics of the aquifer, without considering the type and intensity of human activities at the surface (Vrba & Zoporozec 1994). Although the vulnerability of an aquifer to contamination is based not only on hydrogeological factors but also on land-use factors (Vrba & Zoporozec 1994), the hydrogeological factors would not be expected change appreciably over time, whereas land use could. For the sustainable management and quality protection of groundwater resources, an assessment of intrinsic vulnerability should be performed for any aquifer area in order to use this information as an indicator of aquifer vulnerability and the need for detailed investigations. Particularly in low-lying permeable coastal aquifers, where the groundwater level is close to the ground surface, a small increase in groundwater recharge and sea-level rise may increase the groundwater levels and consequently increase the aquifer vulnerability.

A shallow, unconfined, coastal aquifer in southern of Finland is confronting these issues in an attempt to maintain water quality within the drinking water standards in the long term. A rise in the sea level due to global climate change would cause some parts of the coastal aquifer to be below the sea level, compromising groundwater quality due to seawater intrusion. This, together with the predicted increase in precipitation, would increase groundwater recharge and raise the groundwater level, consequently contributing to the potential deterioration of groundwater quality or potential flooding in the low-lying aquifer area.

A number of methods have been used to assess the intrinsic vulnerability of aquifers. Among these, DRASTIC (Aller et al. 1987), SINTACS (Civita 1994), GOD (Foster 1987) and the AVI (Van Stempoort et al. 1993) are well-known and suitable methods for aquifers in clastic sedimentary environments. The DRASTIC method is usually used to determine the vulnerability of groundwater to contamination from anthropogenic sources from the ground surface. However, it does not take into account factors associated with watercourses. SINTACS is a modified DRASTIC method with more options for the weight strings, including factors associated with human activities and watercourses, while the rating system of each parameter is still preserved as in the original DRASTIC (Civita 1994). For coastal aquifers, however, both DRASTIC and SINTACS have no parameters to determine contamination from seawater intrusion, which is a different and more complicated process compared to contamination via sources from the ground surface (Werner et al. 2013). The GALDIT index (Chachadi et al. 2003, Lobo-Ferreira et al. 2007), a system of weights and ratings similar to DRASTIC and SINTACS, is a well-known method for assessing the vulnerability to seawater intrusion of coastal aquifers. The GALDIT vulnerability index map indicates the aquifer area along the coastline that is most likely to be affected by seawater intrusion and provides recommendations for detailed site investigations of aquifer areas. Although GALDIT does not take into account the rate of groundwater withdrawal relative to the total amount of freshwater recharge to the aquifer, or the freshwater–saltwater interface in the seawater intrusion process, the simplicity of this method makes it attractive for assessing aquifer vulnerability to seawater intrusion (Ivkovic et al. 2013), and it has been used in many coastal aquifer areas around the world (e.g. Chachadi et al. 2003, Chachadi & Lobo-Ferreira 2007, Lobo-Ferreira et al. 2007, Dörfliger et al. 2011, Najib et al. 2012, Kura et al. 2015, Recinos et al. 2015, Allouche et al. 2015, Trabelsi et al. 2016).

In Finland, shallow aquifers are derived from Quaternary sediments deposited during the Weichselian glaciation and deglaciation. The sediments consist of glacial gravel, sand, till and clay, and in some areas of postglacial littoral gravel, sand and clay. The aquifers are very often located next to watercourses such as lakes or rivers (Okkonen & Klöve 2010), or human activities (e.g. urban areas, industries, highways). The groundwater level of a permeable shallow aquifer is often quite near the ground surface, with an average depth of about 2–5 metres. Therefore, it responds rapidly to changes in groundwater recharge, which cause the aquifer be more vulnerable to contamination. The assessment and mapping of aquifer vulnerability should be urgently carried out and incorporated into the groundwater protection process. However, a suitable vulnerability assessment method that can be applied with the same standard to all shallow aquifers in Finland is still needed.

1.3 Research objectives and hypothesis

The hypothesis of this study was that the potential impacts of climate change on the groundwater resources of shallow, unconfined, low-lying coastal aquifers could cause risks not only due to changes in recharge patterns (resulting from changes in precipitation and temperature), but also from the sea-level rise, making coastal aquifers more vulnerable to these changes than other aquifers inland. In addition, the risks from human activities in aquifer areas emphasize groundwater vulnerability. Another hypothesis was that because Finnish aquifers are located in a cold snow-dominated region, seasonal variation in groundwater recharge will be strongly affected by climate change in terms of the timing and amount of groundwater recharge, which will affect both the level and quality of groundwater. This thesis study aimed to investigate and assess the vulnerability of groundwater to contamination in a shallow, unconfined, low-lying coastal glaciogenic aquifer in Hanko, southern Finland, under both present conditions and future climate change and variability.

The main objectives of the research were:

1) To clarify the current condition of the coastal Hanko aquifer, located in a cold snow-dominated region in southern Finland, in terms of the origin of groundwater and groundwater chemistry as well as groundwater recharge and groundwater–surface water interactions (with the Baltic Sea and a lake named Sandöträsket). This includes the temporal and spatial variations in groundwater and surface water geochemistry in different recharge periods;

2) To assess the impact of climate change and variation, and of sea-level variation on groundwater recharge (the amount and timing of aquifer recharge and its effects on groundwater geochemistry), the groundwater level and surface leakage, and groundwater quality in the Hanko aquifer;

3) To assess the intrinsic vulnerability of groundwater in the Hanko aquifer to contamination from sources on the ground surface and seawater intrusion under current conditions and under climate change scenarios, and identify the climate change variables that have the greatest impact on the groundwater table, and consequently on the vulnerability of shallow unconfined low-lying coastal aquifers, as well as to determine the most suitable method for assessing the vulnerability of these aquifers.

This thesis consist of a compilation of three individual papers and the summary of their results. The work processes and the methods used in Papers I to III and data transferred between those papers are summarised in Figure 1. The research methods and materials are briefly described in Chapter 3. Because of the relatively low density of the Baltic Sea and the lack of predicted data on density changes in this water body under different climate change scenarios, density-dependent models were not used. Only the Baltic Sea level rise and fluctuation estimated for various climate change scenarios can be used to estimate the impacts of the Baltic Sea level fluctuation and its impacts, together with those of changes in climate variables, on groundwater and interactions between the Baltic Sea and aquifers connected to it.

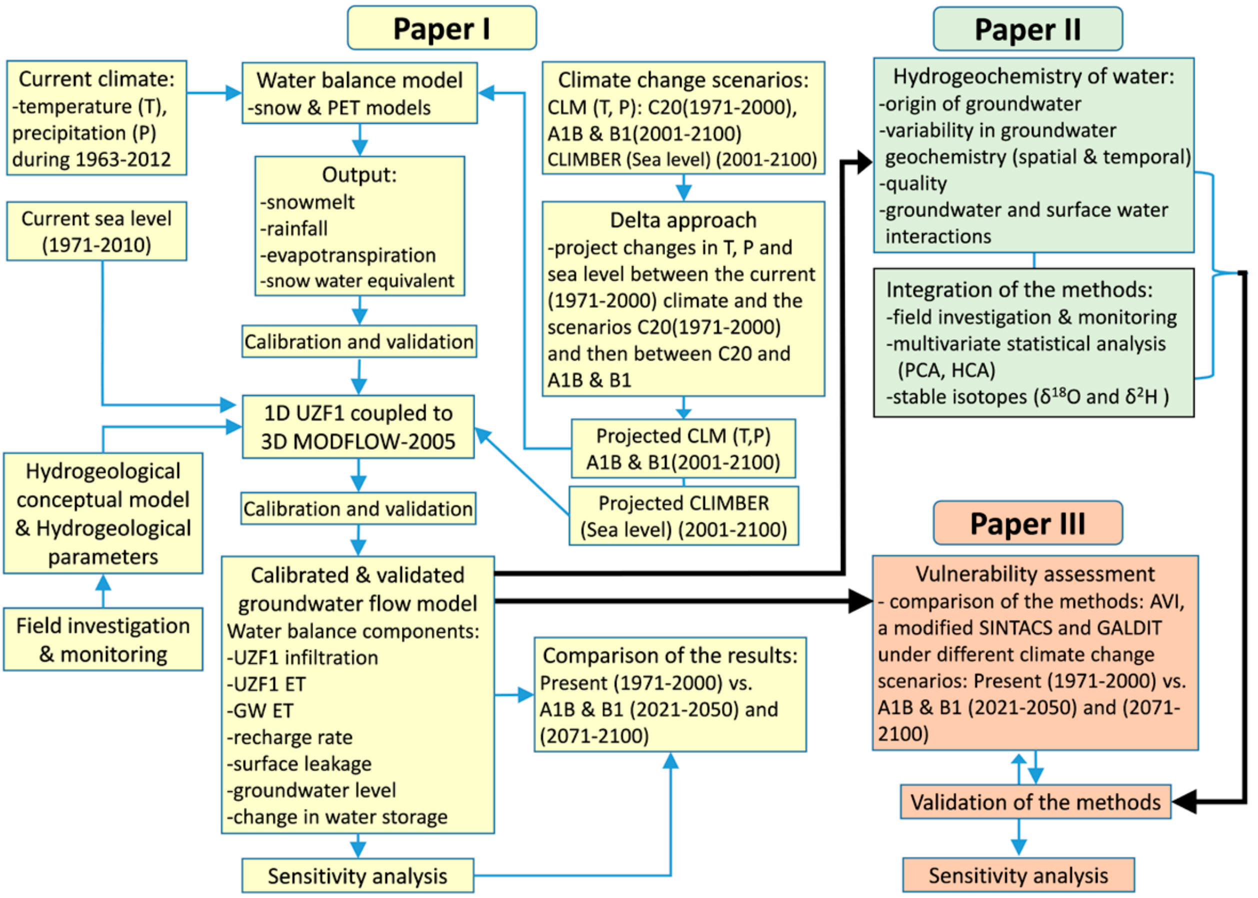

Fig. 1. Schematic diagram showing the work processes and the methods used in Papers I to III and data transferred between those papers.

2 DESCRIPTION OF THE STUDY SITE

2.1 Shallow aquifers in Finland

The classified important groundwater areas in Finland are restricted to Quaternary deposits (Gustafsson et al. 2006, Britschgi et al. 2009), which provide an important groundwater resource for the public water supply of the municipalities. Shallow Quaternary aquifers mainly consist of permeable sand and gravel deposits. About 7% of the land area in Finland is covered by glacial and deglacial deposits (Salonen et al. 2002) (Fig. 2). The most significant aquifers in southern Finland are in sandy and gravelly eskers, as well as in the Salpausselkä ice-marginal end moraine deposits.

Unlike the other aquifers in Europe, the configuration of the shallow aquifers in Finland has, to a limited extent, been caused by sand and gravel deposits in the proximal parts of subaqueous fan and subglacial tunnel sediments during the glaciations and deglaciations, and is partly associated with the thick clay or fine-grained sediment layers or till deposits. The groundwater table is often quite close to the ground surface, with the depth to groundwater varying from less than a metre to more than thirty metres, and averaging about 2–5 metres. Approximately 300 out of the total of 6000 classified shallow groundwater areas in Finland (excluding Åland) are located 100 m or less from the shore of the Baltic Sea (Hertta database, SYKE 2013). The Baltic Sea is one of the largest brackish water areas in the world (EEA 1999), with low salinity varying from 3–7% in the Gulf of Finland (Alenius et al. 1998, UNEP 2005, Fagerlund 2008).

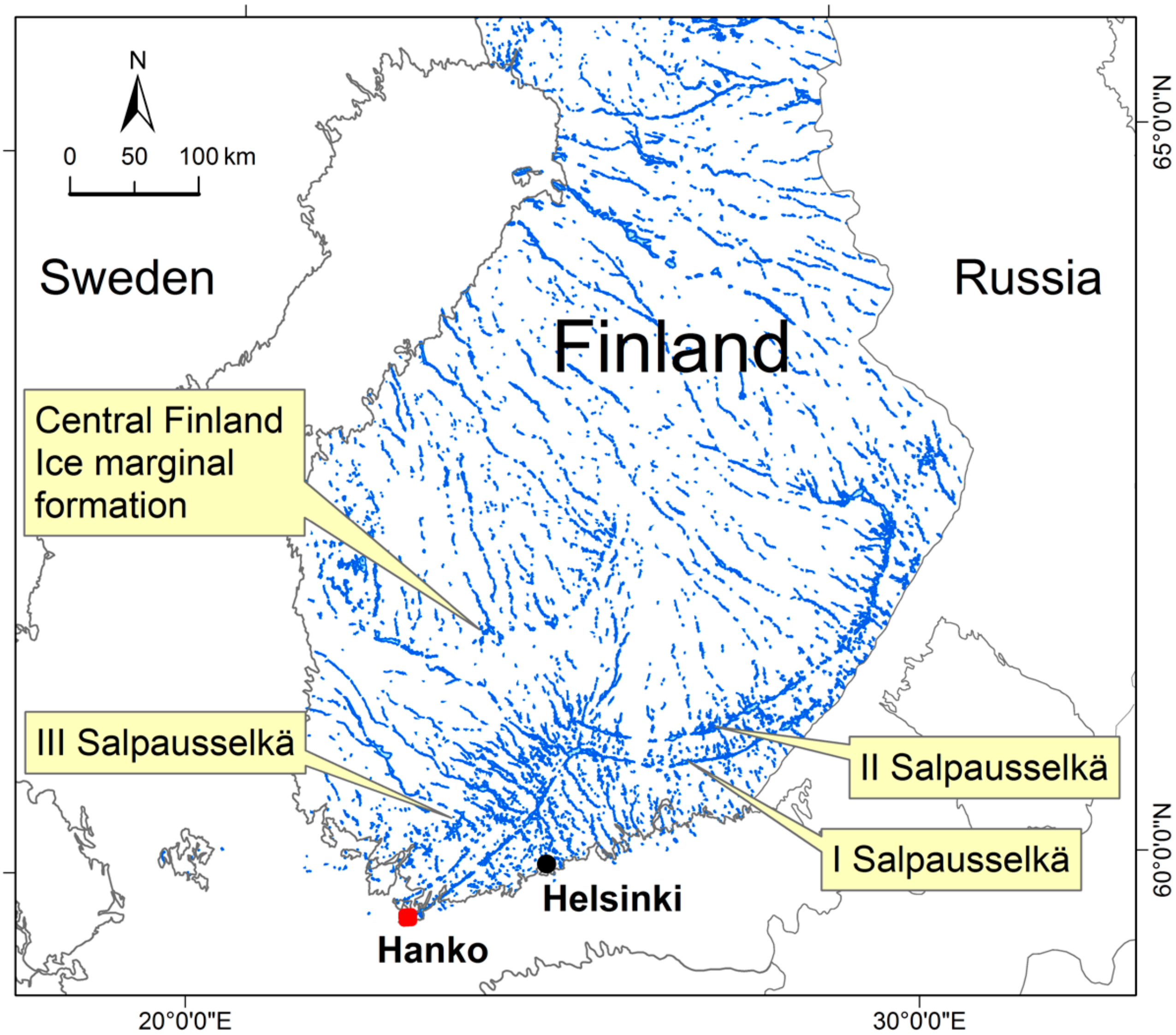

Fig. 2. Map of Quaternary sand and gravel deposits (in blue) in southern Finland, the most important shallow groundwater resources in Finland (Groundwater area © SYKE, Basemap Database © National Land Survey of Finland 2016). The three Salpausselkä formations are marked on the map.

2.2 The shallow, unconfined, low-lying coastal aquifer in Hanko, southern Finland

The case study area is located on the Hanko peninsula on the southern coast of Finland at approximately 59°53"N 23°10"E (Fig. 3). The shallow, unconfined, low-lying coastal aquifer in Hanko consists of porous gravels and sands of an ice-marginal end-deposit, and is bounded by the Baltic Sea. It is an important source of water for the residents of the town Hanko and the local industries. Total yield of the aquifer is 18 700 m^3 d^{-1} (FCG Suunnittelu ja Tekniikka Oy 2013). The economy of Hanko town is based on services (61%) and industry (38%), and the population in 2016 was 9109 (www.hanko.fi). Hanko is also a popular summer resort, where the population increases considerably during the summer due to the arrival of holiday home owners and tourists. The Hanko area belongs to the temperate coniferous-mixed forest climate zone with cold, wet winters (Essenwanger 2001). The mean annual temperature is 6 °C, with mean minimum and maximum temperatures of -4.2 and 16.6 °C, respectively. The average annual precipitation was 620 mm during the period 1971–2000. Forest, mainly consisting of Scots pine (*Pinus sylvestris*), is the main land cover in the aquifer area (approximately 80% of land cover). Additionally, the existing potential anthropogenic impacts from human activities in the area, namely gravel excavation pits, local industries, and salt (NaCl) application for de-icing on the highway that runs through the middle of the groundwater area, could pose a contamination risk to groundwater quality.

2.3 Geology and hydrogeology of Hanko aquifer

The Quaternary deposits in the Hanko area are underlain by the basement of the Precambrian crystalline igneous and metamorphic rocks (Fig. 3). The Precambrian bedrock mainly consists of granite, quartz diorite and granodiorites, forming a sharp unconformity with the Quaternary deposit with some outcrops in the area (Kielosto et al. 1996). The aquifer in the study area is in the First Salpausselkä ice-marginal formation, deposited during the Weichselian and Holocene deglaciation of the Scandinavian Ice Sheet (Fyfe 1991, Saarnisto & Saarinen 2001). The formation consists of gravel, sand, glacial till, silt and clay, and of postglacial littoral gravel, sand and clay (Fig. 3) that was originally deposited as sub-glacial outwash fan deposits (Fyfe 1991).

The primary ice-marginal formation in Hanko was formed in deep water as a low narrow ridge (Fyfe 1991). When the ice sheet withdrew from the area, this deep-water deposit was covered by fine-grained sediments, silt and clay layers, of the Ancylus Lake and Littorina Sea. The sea level has been regressive since deglaciation because of isostatic land uplift. The primary deposit of the First Salpausselkä formation was exposed to sea waves and also to wind (Kielosto et al. 1996). The well-sorted gravels indicate reworked materials from the high energy of waves and storm activities, and are found over a large area in Santala, while the fine sand from aeolian deposits covers a large area in the east (Fig. 3) (Fyfe 1991, Kielosto et al. 1996). The lake and wetlands in the middle of the aquifer are located in a depression that forms part of the First Salpausselkä formation and the sand dune terrain. The lake has a surface area of about 1.8 km^2, with an average depth of approximately 1–2 m.

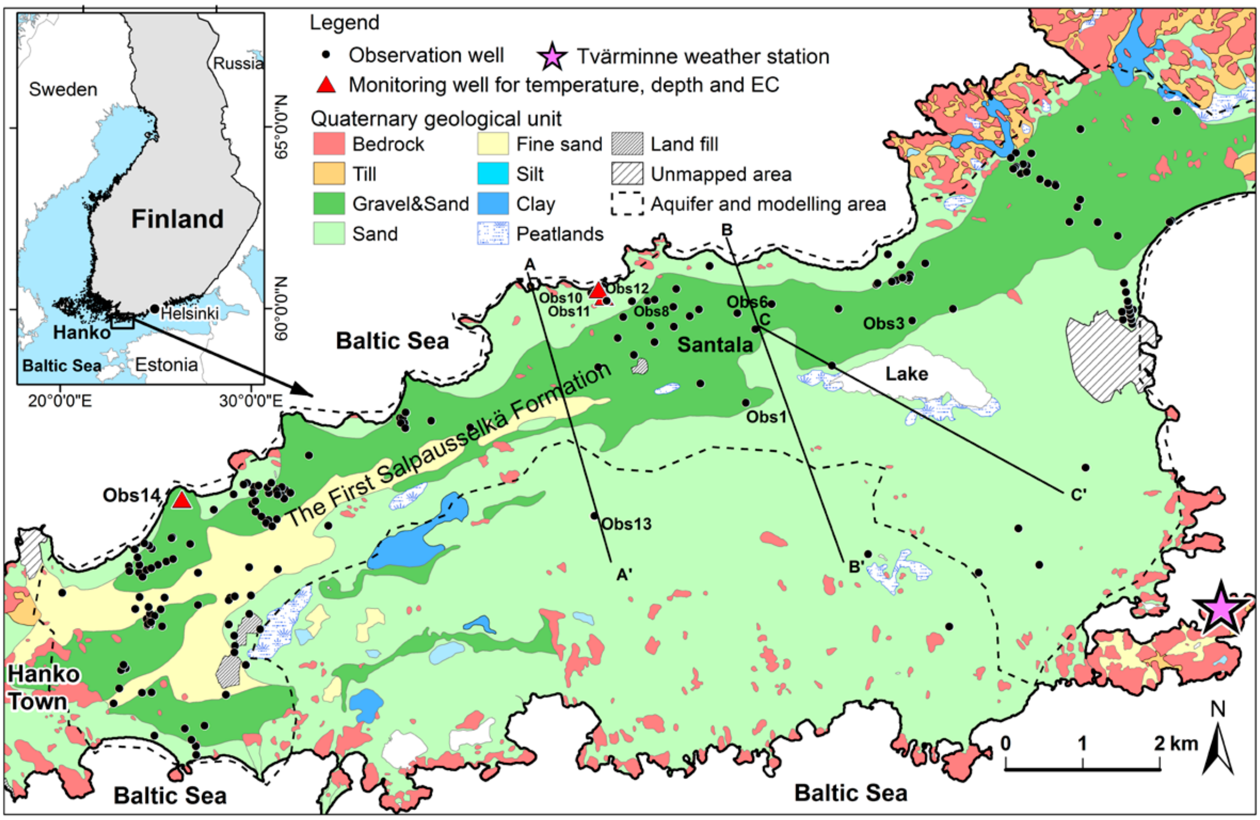

Fig. 3. Location and Quaternary geological deposit map of the study area in the eastern Baltic Sea region. Cross-section lines A–A' to C–C' are presented in Figure 5. (Quaternary Deposit Database © Geological Survey of Finland, Basemap Database © National Land Survey of Finland 2016). Modified from Paper III.

The topography of the study area varies between 10–14 m a.s.l. along the northern ridge of the First Salpausselkä formation, to less than two metres along the northern coastline, while in the south and southeast the elevation gradually decreases to 5–7 m a.s.l. (Fig. 4). The shallow aquifer in Hanko is unconfined, with the thickness of the Quaternary deposits varying from less than

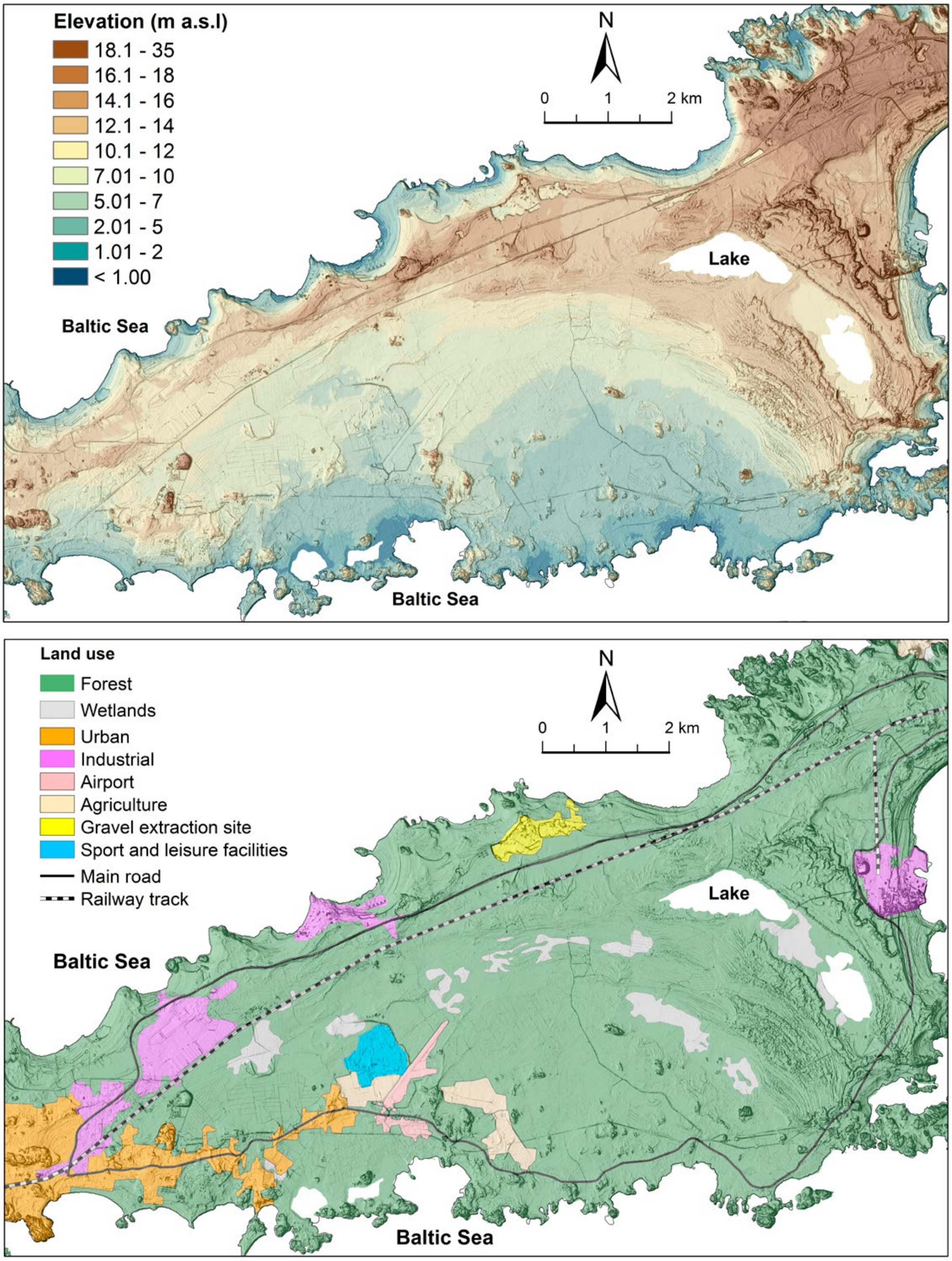

Fig. 4. Elevation model (top) and land-cover and land-use map (bottom) of the Hanko area. (Basemap Database, Topographic Database, and Corine land cover © National Land Survey of Finland 2016).

one metre to 75 m, with the average thickness being about 25 m. The sediments are generally thick on the western side, in a NE–SW direction, conforming to the First Salpausselkä formation, and their thickness decreases eastwards to less than one metre in the eastern coastal area (Fig. 5). The groundwater table varies between 2–10 m below the ground surface in the inland area, and is less than 2 m below the ground surface in the coastal area, where groundwater discharges into the Baltic Sea. In many parts of the aquifer, the groundwater level is close to the ground surface, and the water intake wells are located along the coastline, where the groundwater level may often fall below the sea level. According to the results of well testing and soil sample analysis, the hydraulic conductivity of the aquifer varies from 0.3–4.8 m d^{-1} in silty sand and fine sand, up to 100 m d^{-1} in sand and gravel (Luoma & Pullinen 2011). Groundwater recharge mainly occurs twice a year, during the spring (late March to early April) and late autumn (November to early December) from the infiltration of snowmelt and rainfall, respectively. Groundwater mainly flows northward into the coastal area and also towards the south-southeast into wetlands and peatlands, as well as towards the Baltic Sea in the east. The groundwater level rapidly responds to a rise in the sea level, as well as to recharge from the spring snowmelt and rainfall (Backman et al. 2007, Luoma et al. 2013).

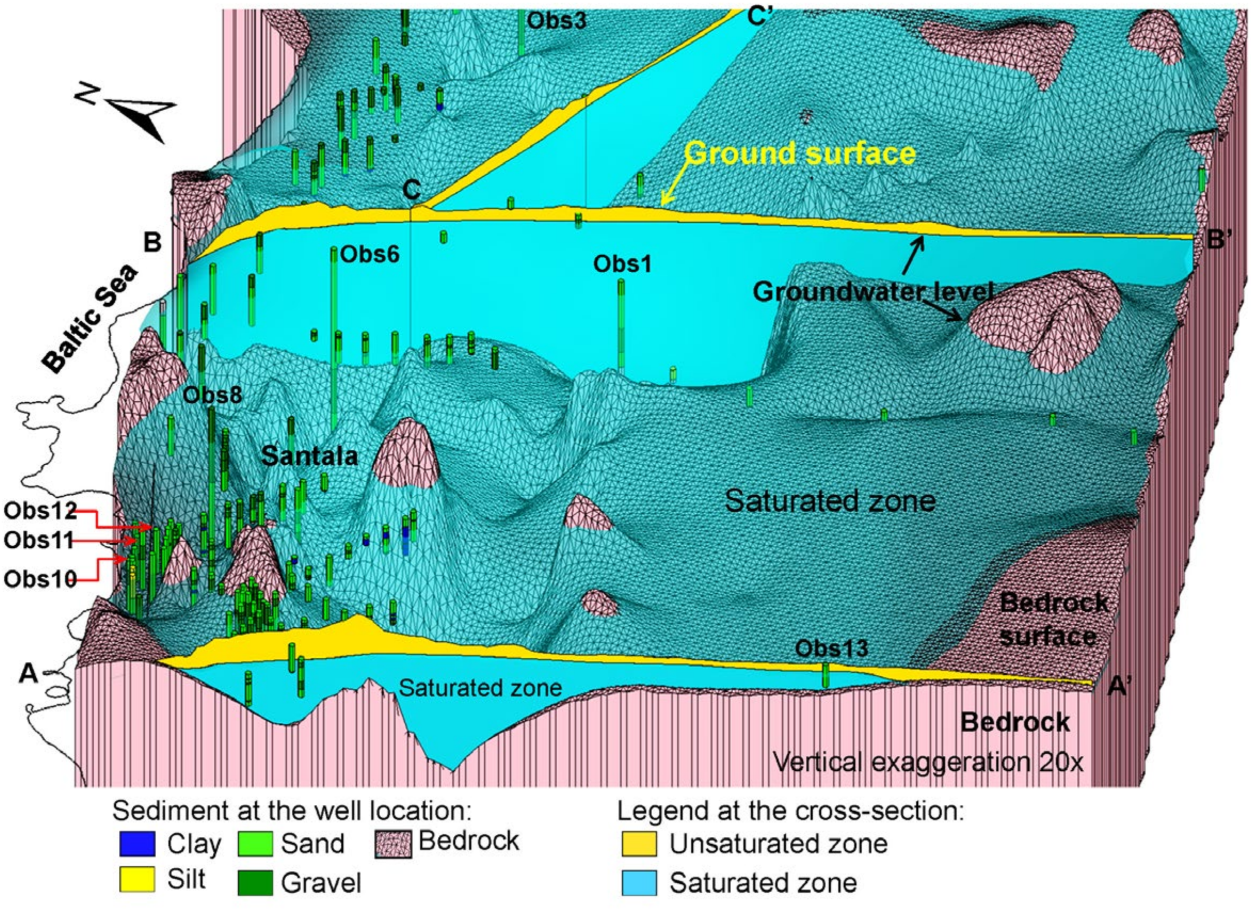

Fig. 5. Visualisation of the bedrock surface, groundwater level and sediments at drilled wells in the Santala area. Cross-section lines A–A', B–B' and C–C' represent the thicknesses of saturated and unsaturated zones of the Quaternary sediment. The locations of cross-section lines and observation wells (Obs) are indicated in Figure 3. Figure from Paper III.

3 MATERIAL AND METHODS

This thesis study involved the integration of multiple methods, which can be divided into four types: 1) numerical groundwater flow modelling; 2) field investigation (including down-hole profile logging, water sampling and well monitoring), together with chemical and stable isotope analysis; 3) statistical analysis; and 4) groundwater vulnerability assessments. The methods used and analyses performed in this thesis study are briefly described in this section. Full descriptions can be found in Papers I–III.

This work started with an assessment of the impacts of climate change and sea-level rise on groundwater recharge, groundwater level and surface leakage in the shallow, unconfined, low-lying coastal aquifer in Hanko, the case study area, in both present and predicted future conditions by using groundwater modelling as an evaluation tool. At this stage, a detailed 3D geological model was constructed for the Hanko aquifer area in order to provide the geological and hydrogeological framework for the 3D groundwater flow model and the parameters used for the groundwater intrinsic vulnerability index mapping in the later stage. This was followed by an investigation of the groundwater conditions, including information on the groundwater origin, groundwater–surface water interaction and groundwater quality, either naturally or following the possible impacts of anthropogenic sources. Finally, an assessment was carried out of groundwater vulnerability to either contamination from sources on the ground surface or seawater intrusion under the present conditions and future climate change scenarios.

3.1 Numerical groundwater modelling (I, III)

3.1.1 Coupling UZF1 and MOFLOW for groundwater flow simulation

Groundwater recharge is an important process in maintaining groundwater levels and the sustainability of groundwater resources. It is also an important parameter for aquifer vulnerability assessment. However, the estimation of groundwater recharge is one of the most challenging tasks in groundwater study and groundwater flow modelling, especially the modelling of groundwater under future climate change scenarios. An appropriate method is needed to estimate recharge from the percolation of precipitation at the ground surface down through the unsaturated zone to the groundwater table.

In this thesis, the 1D Unsaturated-Zone Flow (UZF1) Package (Niswonger et al. 2006) was coupled with 3D groundwater flow model MODFLOW-2005 (Harbaugh 2005) to simulate the flow from the unsaturated zone through the aquifer, using the infiltration water values produced by the snow and potential evapotranspiration (PET) models. The impact of soil frost on water infiltration was considered to be minimal, particularly in the Hanko aquifer where the infiltration can take place even at a surface temperature of −2 °C (Hänninen & Äikää 2006). In cold, snow-dominated regions, the impact of soil frost on water infiltration is generally an issue, but in permeable, sandy aquifers recharge can occur even in partially frozen soil (Sutinen et al. 2007, Okkonen & Kløve 2011). The simulation results from the UZF1 coupled with the MOFLOW approach provided not only an estimate of groundwater recharge from the groundwater surface through the unsaturated zone flow to the groundwater level, but also information on groundwater discharge or the surface leakage zone in coastal and low-lying aquifer areas.

Recharge estimation and groundwater flow modelling were performed in three consecutive simulation processes. First, the snow and PET models were used to calculate the surface water available for infiltration from the precipitation input data used in the UZF1 package. The snow and PET models were calculated independently from UZF1 and MODFLOW by utilising the water balance model after Vehviläinen (1992) where the snowmelt water and rainfall were estimated by using daily precipitation and temperature data, and the PET was predicted using a temperature-based method after Hamon (1963). The calibration and validation of the snow and PET models were performed using the observed snow water equivalent data during the periods

1963–2001 and 2002–2012, respectively. Second, the infiltration rate, flow in the unsaturated zone and groundwater recharge were simulated using the UZF1 package run in MODFLOW-2005, whereupon the well-calibrated 3D groundwater flow model MODFLOW-2005 was used to simulate and predict the potential impacts of climate change on groundwater recharge under the future climate change scenarios in the Hanko area. Finally, the A1B and B1 climate and sea-level rise (high and medium) scenarios were applied for two periods, 2021–2050 and 2071–2100. The water balance in the model domain was computed and compared with the reference period of present-day climate conditions (1971–2000) in order to assess the potential change in groundwater resources in the future.

3.2 Simulated scenarios (I, III)

3.2.1 Climate data and climate change scenarios

Daily precipitation and temperature data during the period 1963–2010, measured at the Tvärminne weather station, were obtained from the Finnish Meteorological Institute (FMI). Snow water equivalent data for the same period, measured at a station in the Santala area, were obtained from the Finnish Environment Institute (SYKE). Trend analysis was carried out for the temperature and precipitation data during the period 1968–2010 using the Mann-Kendall and Sen non-parametric tests (Gilbert 1987). Climate model data on two greenhouse gas emissions scenarios, A1B and B1, for the period 2001–2100 and a simulation of present climate 1971–2000 from the regional climate model CLM (Climate Limited-area Modelling community of the German Meteorological Service) were obtained from the World Data Center for Climate, Hamburg (World Data Center for Climate 2011). The boundary conditions of the CLM model were derived from the ECHAM5/MPI-OM global climate model of the Max Planck Institute for Meteorology, which contributed to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (CMIP3 (IPCC AR4)) (Hollweg et al. 2008). The CLM model covers Europe with a grid resolution of 18×18 km^2 where four data points fall over the Hanko area. Daily precipitation and temperature data were derived from the average values of those four points and represent the climate data over the model domain area. The Delta approach was used to project changes in temperature and precipitation between the current climate and the scenarios data (Veijalainen et al. 2010, Okkonen 2011). The A1B emissions scenario predicts a possible future world of very rapid economic growth, with the global population peaking in the mid-century and the rapid introduction of new and more efficient technologies, with a balance across all energy sources. The B1 scenario envisages a convergent world with a rapid change in economic structures towards a service and information economy and the introduction of clean and resource-efficient technologies. The climate simulation data for the 30-year period from 1971–2000 were used for comparison with the measured data for Hanko obtained from the Finnish Meteorological Institute (FMI). For comparison, two climate parameters (temperature and precipitation) from the A1B and B1 scenario data were grouped into two 30-year time spans: 2021–2050 and 2071–2100.

3.2.2 Sea-level data and sea-level rise scenarios

Daily sea-level data for the period 1971–2010 were obtained from Marine Research, FMI. During 1971–2000, the mean sea level varied between -0.49 and +0.58 m, with an average level of -0.02 m. The sea-level rise scenarios used were A1B and B1 (high and medium regionalized) from the CLIMBER model, with compensation for the vertical post-glacial land movement component for the period 2000–2100 with the baseline being 1995 (Petoukhov et al. 2000, Ganopolski et al. 2001). Trend analysis was also carried out for the seawater level data during the period 1971–2010 using the Mann-Kendall and Sen non-parametric tests.

3.2.3 Water balance estimation

The water balance components from the groundwater flow simulations consisted of infiltration rate in the unsaturated zone (UZF1 infiltration), evapotranspiration in the unsaturated zone

(UZF1 ET) and saturated zone (GW ET), surface leakage, the recharge rate, and the change in water storage. For comparison, each simulation result was summarized for two periods, 2021–2050 and 2071–2100, which were used to compare with the present (1971–2000) data.

3.3 Water sampling and analysis (II)

3.3.1 Field investigations, water sampling, and water level monitoring

Field investigations consisted of down-hole profile logging and field measurement of water samples. The profile logging was performed in order to investigate the vertical distribution of physical and chemical parameters of groundwater at the screen intervals of the observation wells, and to validate the water sampling depths based on the results of these logs. If there were variations in the profile, partition samples were taken by placing an inflatable packer at a discrete depth delineating the selected zones, and a single groundwater sample was collected at a time, beginning with the top section and continuing downwards to the bottom section. The measurement was performed by using either a WTW P4 instrument (during the winter) or a YSI Professional Plus (IP-67), a multi-parameter recording device, for the measurement of EC, pH, T, O_2 and Eh. Dissolved carbon dioxide (CO_2) was measured in the field by using a colorimetric titration method (Csuros 1994) with 0.02N NaOH, while alkalinity was measured by using automatic potentiometric titration immediately upon arrival of the samples at the laboratory.

Water sampling was carried out four times, during the winter, spring, summer and autumn of 2012, in order to study the variations in the geochemistry and stable isotope composition of water in different seasons over the year. Water samples were collected from 15 sites, including water samples from 12 groundwater observation wells in Santala, the lake above the aquifer, the Baltic Sea, and a water intake well (Fig. 1 in Paper II). In total, 26 samples were taken for chemical analysis and 59 samples for the analysis of the stable isotope compositions of oxygen and hydrogen. In addition, water chemical analysis results for six water samples taken during spring 2010, as well as groundwater monitoring data (depth (D), temperature (T), electrical conductivity (EC) and field measurement data, including D, T, EC, pH, dissolved oxygen (O_2), redox potential (Eh) and dissolved carbon dioxide (CO_2) for 12 wells in the Hanko area obtained during the years 2009–2010, were used to support the interpretation.

The groundwater level recorded in observation wells is an important parameter that represents the distribution of the hydraulic head, which can be used to characterize the direction and magnitude of the hydraulic gradient. It is used for the analysis of groundwater–surface water (lake, seawater) interaction, groundwater recharge estimation, the calibration of groundwater modelling, and for long-term monitoring. Groundwater level can be analysed for trend to identify the impacts of climate variability on groundwater recharge and groundwater resources. In this thesis study, water level monitoring was carried out for eight groundwater observation wells from March to November 2012 and in the lake at Hanko from September to November 2012. Measurement was performed by installing a Schlumberger Mini-Diver data logger and pressure transducer at the same sampling depths. Three wells located near the coastline area were also monitored for T, D and EC. Lake water and five inland wells, which were situated far from the coastline and the water intake well, were monitored for T and D. The monitoring of T, D and EC in wells located along the coastline was performed to investigate the groundwater–surface water interaction between the Baltic Sea and aquifers and the temporal variability in groundwater discharge into the sea and/or seawater intrusion into the aquifer. A time series of climate data (temperature and precipitation) and sea-level recordings in the Hanko area from the same period were obtained from the Finish Meteorological Institute (FMI 2013) and used for comparison.

3.3.2 General water chemistry (II)

The major ions (Ca, Mg, Na, K, HCO_3, Cl, SO_4 and NO_3) and minor elements (Ag, Al, As, B, Ba, Be, Bi, Cd, Co, Cr, Cu, I, K, Li, Mn, Mo, Ni, P, Pb, Rb, Sb, Se, Sr, Th, Tl, U, V, Fe, Si and S), as well as

EC, pH and $KMnO_4$ consumption, were analysed from water samples to identify the main ion composition of different water types (groundwater, lake water and seawater) in different seasonal periods, and to measure the degree of impact of seawater intrusion at wells located along the coastline compared with inland aquifers, as well as the impact of potential contamination sources from human activities in the study area.

3.3.3 Stable oxygen and hydrogen isotopes (II)

The stable isotopes ^{18}O and ^{2}H are commonly used in studies on groundwater flow and the interaction of groundwater and surface water. These stable isotopes are effective tracers that can be used to identify the origin of water as well as the mixing processes of isotopically distinct water masses and evaporation in surface water reservoirs (Gonfiantini 1986, Richter & Kreitler 1993, Taylor & Howard 1996, Clark & Fritz 1997, Kendall & McDonnell 1998, Allen, 2004, Faure & Mensing 2005). The recent regional isotopic composition of both atmospheric precipitation and groundwater are well known in southern Finland (Kortelainen 2007, Kortelainen & Karhu 2004). Based on monthly isotopic values of oxygen and hydrogen in Finnish precipitation, the national scale meteoric water line ($^{2}H = 7.67\ ^{18}O + 5.79‰$) was established by Kortelainen in 2007. The line agrees well with local lines derived for the southern coast of Finland (Kortelainen 2007, 2009) and could consequently be applied in this study. In temperate climates such as in Finland, the isotopic composition of the local groundwater closely follows that of local precipitation (Kortelainen 2007, Kortelainen & Karhu 2004). The stable isotope method has been widely applied in Finland, especially to evaluate natural groundwater–surface water interaction (Rautio & Korkka-Niemi 2011) and artificially enhanced surface water infiltration into aquifers (Kortelainen & Karhu 2006, Hendriksson et al. 2012). In this study, the stable isotope ratios of ^{18}O and ^{2}H were used to determine the origin of groundwater and the interaction of groundwater and surface water.

3.3.4 Statistical analysis (II)

Data correlations and statistical analyses were performed using the IBM SPSS statistical package (IBM SPSS Statistics 2013). The correlations between water chemistry variables were carried out by using the Pearson correlation coefficient to identify the relationships between variables among the water sampling sites. Two multivariate statistical approaches, principal component analysis (PCA) and hierarchical cluster analysis (HCA), were used to group the water samples and to determine the variables that represent the controlling factors behind the geochemistry of water samples. In addition, the integration of PCA and HCA with conventional classification of groundwater types, as well as with the hydrogeochemical data, provided useful tools to identify the vulnerable groundwater areas representing the impacts of both natural and human activities on water quality, and to provide understanding of the complex groundwater flow system to support aquifer vulnerability assessment and groundwater management in the future.

PCA is used to extract components representing the information contained in the data that explain the pattern of correlations and differences within a group of variables (Korkka-Niemi 2001, IBM SPSS Statistics 2013). The number of components was extracted by PCA with varimax rotation based on Kaiser normalisation. While HCA is a classification method that reveals natural groupings or clusters within a data set by reorganizing the data into homogeneous groups and linking the two most similar clusters until all of the variables are joined in a complete classification tree (Korkka-Niemi 2001, IBM SPSS Statistics 2013). The results of HCA are presented in a dendrogram, which is constructed using Ward's method (Ward 1963) with the Euclidean distance as a measure of similarity between the samples. Ward's method is one of the most widespread hierarchical clustering methods for the classification of hydrogeochemical data by using the minimum variance to evaluate the distances between the clusters (Güler et al. 2002, Cloutier et al. 2008, Templ et al. 2008).

3.4 Groundwater vulnerability assessment (III)

3.4.1 Comparison of vulnerability assessment methods

In this thesis study, three intrinsic vulnerability mapping methods were used that were considered suitable for aquifers in clastic sedimentary environments: a modified version of SINTACS, the AVI and GALDIT. These were applied and compared to identify the most suitable method for the vulnerability assessment of the shallow, unconfined, low-lying coastal aquifer at Hanko. SINTACS was selected because it has more options than the original DRASTIC method (Aller et al. 1987, Civita 1994) for the weight strings, including those factors associated with human activities and watercourses that are commonly found in shallow groundwater areas in Finland. In addition, the rating classifications of three of the seven parameters in SINTACS (soil media, aquifer media and attenuation capacity of the unsaturated zone) were modified based on the superficial deposit map of Finland to make the index more suitable for glacial aquifer deposits and deglaciation depositional environments compared with the parameters from the original SINTACS.

The AVI is simpler than SINTACS, with only two parameters required for the analysis (Van Stempoort et al. 1993). It provides a quick vulnerability assessment and indicates the need for detailed investigation. The AVI was selected in order to compare with SINTACS to evaluate the effect of the number of parameters inputted on the vulnerability indices. However, neither SINTACS nor the AVI have parameters to determine contamination from seawater intrusion. Thus, GALDIT was selected for the intrinsic vulnerability assessment of seawater intrusion of the coastal aquifer and compared with SINTACS and the AVI.

The SINTACS and GALDIT methods are based on index weight rating (Civita & De Maio 2004, Chachadi & Lobo-Ferreira 2007) and the overlay analytical function using the ArcGIS/ArcMap program, while the AVI method is based on the type and thickness of the aquifer media above the groundwater level. Index models are generally used in aquifer vulnerability assessment instead of numerical groundwater flow and transport models. This is because they are easy to apply and the index maps can be simply overlaid upon and integrated with thematic maps such as land-use maps or hydrogeological maps in order to provide information to support the decisions of land users or land-use managers for groundwater risk assessment in an area (Ivkovic et al. 2013). A brief description of each method is given below.

3.4.1.1 SINTACS and the modified SINTACS

The intrinsic vulnerability mapping SINTACS method (Civita & De Maio 2004) is a parametric system with rating scores and weights for seven parameters: depth to the groundwater table (*So*), effective infiltration (*I*), unsaturated zone attenuation capacity (*N*), soil attenuation capacity (*T*), hydrogeological characteristics of the aquifer (*A*), hydraulic conductivity (*C*) and topographical slope (*S*), and the overlay analytical function using the ArcMap program. Each parameter was rated based on its characteristics and susceptibility to groundwater contamination from 1 (the lowest vulnerability) to 10 (the highest vulnerability). In each grid cell, the assigned parameter ratings were then multiplied by the weight strings, which corresponded to one of six hydrogeological environments, including Normal Impact, Severe Impact, Drainage, Karst, Fissured and Nitrates. Each weight string was assigned a value from 1 to 5, with the most significant factors receiving a weight of 5 and the least significant a weight of 1. The final vulnerability index in each grid cell was the sum of the scores for the seven parameters and was obtained by superposition of the seven thematic maps (Equation 1):

$$\text{SINTACS index} = SorSow + IrIw + NrNw + TrTw + ArAw + CrCw + SrSw \quad (1)$$

where *r* is the rating and *w* is the weight string. The final vulnerability index score was divided into vulnerability classes (very high, high, medium, low and very low) to produce a final vulnerability SINTACS index map of aquifer area. The classification category was varied depending on the number of weight strings applied. A possible minimum value of 26 to a possible maximum value of 260 represents a relative measure of groundwater vulnerability. The higher the

Table 1. SINTACS parameters and ratings. Modified parameters are indicated by *.

Parameter	**S**	**I**	**N***	**T***	**A***	**C**	**S**
Rating	Depth to water (m)	Recharge (mm yr^{-1})	Unsaturated zone attenu-ation capacity	Soil media	Aquifer media	Hydraulic conductivity, K (m d^{-1})	Topography (slope, %)
1	> 40	0-24	Confining layer, clay	clay lens	clay lens	< 0.0043	26-30
2	24-40	25-42	Silt, silty/ sandy/ gravelly clay	Silty / sandy / gravelly clay	Silt, silty/ sandy/ gravelly clay	0.0043-0.043	22-25
3	16-24	43-66	Silt & clay	Clay loam	Gyttja	0.043-0.17	19-21
4	12-16	67-92	Fine-grained till	Silt, silty loam	Fine-grained till	0.17-0.61	16-18
5	8-12	93-110	Sandy, gravelly till	Loam	Sandy, gravelly till	0.61-2.59	13-15
6	6-8	111-135	Finer fine sand	Sandy loam	Finer fine sand	2.59-6.48	10-12
7	4-6	136-162	Coarser fine sand	Aggregated clay, loamy sand	Coarser fine sand	6.48-23.33	7-9
8	3-4	163-194	Sand & gravel	Peat	Sand	23.33-62.21	5-6
9	1.5-3	195-235	Gravel	Sand	Sand and gravel	62.21-345	3-4
10	< 1.5	>235	No vadose zone	Thin or absent, gravel	Gravel	> 345	0-2
Weight string	S	I	N	T	A	C	S
Normal	5	4	5	3	3	3	3
Severe	5	5	4	5	3	2	2
Drainage	4	4	4	2	5	5	2

vulnerability index value, the more vulnerable the aquifer is to contamination. In this study, the modification was performed to SINTACS for three parameters: the attenuation capacity of unsaturated zone, the soil media and the aquifer media. This was done by classifying the rating system based on the surficial deposits map of Finland, while the other parameters and weight strings were maintained as in the original SINTACS method. The rating and weight strings of the modified SINTACS are presented in Table 1. Further details of the modified SINTACS parameters are provided in Paper III.

3.4.1.2 Aquifer vulnerability index (AVI)

The aquifer vulnerability index (AVI) (Van Stempoort et al. 1993) is a method for mapping the vulnerability of groundwater based on two parameters: the thickness of each sedimentary unit above the uppermost saturated aquifer (*d*, length) and the estimated hydraulic conductivity (*K*, length/time) of each of these layers. The index is determined from the relationship between these two parameters, as shown in the following equation (Equation 2):

$$\text{AVI} = di \,/\, Ki \qquad \text{for layer 1 to } i. \qquad (2)$$

The AVI has a dimension of time that represents the hydraulic resistance of an aquifer to vertical flow. Based on these hydraulic resistances, the AVI is divided into vulnerability classes (e.g. very high, high, medium, low and very low) to produce a final vulnerability AVI index map of an aquifer area.

3.4.1.3 GALDIT

GALDIT is an intrinsic vulnerability assessment method for assessing the vulnerability of a coastal aquifer to seawater intrusion (Chachadi & Lobo-Ferreira 2001, 2007, Chachadi et al. 2003). Similarly to SINTACS, it is a parametric system with rating scores and weights for six parameters that describe the most important factors controlling seawater intrusion: groundwater occurrence (*G*), aquifer hydraulic conductivity (*A*), the groundwater level above sea level (*L*), distance from the shore (*D*), the impact of the existing status of sea water intrusion (*I*) and the thickness of the aquifer (*T*). Each parameter was rated based on its characteristics and susceptibility to seawater intrusion, the alternative scores being 2.5 (lowest vulnerability), 5, 7.5 and 10 (highest vulnerability). In each grid cell, these assigned rating parameters were then multiplied by the weight strings. The weight strings were assigned a value from 1 (the least significant factor) to 4 (the most significant factor). The final vulnerability index in each grid cell was the sum of the scores of these 6 parameters (Equation 3):

$$\text{GALDIT index} = \frac{\sum_{i=1}^{6} WiRi}{\sum_{i=1}^{6} Wi} \tag{3}$$

where *R* is the rating and *W* is the weight string. The final GALDIT vulnerability index score varies from 2.5 to 10 and is divided into three vulnerability classes: high (>7.5), moderate (5 to 7.5) and low vulnerability (<5). The higher the vulnerability index value, the more vulnerable the aquifer is to seawater intrusion. The rating and the weight strings of GALDIT are presented in Table 2 and paper III.

Table 2. GALDIT parameters and ratings.

Rating	Groundwater occurrence (Aquifer type)	Aquifer hydraulic conductivity ($m\ d^{-1}$)	Height of groundwater level above sea-level (m)	Distance from the shore (m)	Impact status of existing seawater intrusion			Aquifer thickness (saturated) (m)
					Cl^- / [HCO_3^- + CO_3^{2-}] [a]	EC ($\mu S\ cm^{-1}$)	Cl ($mg\ l^{-1}$)	
10	Confined Aquifer	> 40	< 1	< 500	> 2	> 1,000	> 200	> 10
7.5	Unconfined Aquifer	10-40	1-1.5	500-700	1.5 - 2	800-1,000	100-200	7.5 - 10
5	Leaky confined Aquifer	5-10	1.5-2	700-1,000	1 - 1.5	400-800	25-100	5 - 7.5
2.5	Bounded Aquifer b	< 5	> 2	> 1,000	< 1	< 400	< 25	< 5
Weight	1	3	4	4		1		2

[a] In milli-equivalent per million in groundwater
[b] Recharge and/or impervious boundary aligned parallel to the coast

3.4.2 Vulnerability assessment under future climate change scenarios

The greatest increase in groundwater recharge (with an average increase of 33% from the present) and the groundwater level in Hanko (with an average increase of 0.98 m from the present) was predicted from the flow simulation utilising the climate and sea-level rise scenario A1B (2021–2050) (with the predicted sea level at +0.13 m). Moreover, the groundwater level fluctuation pattern in Hanko shows clear seasonal variations, where the maximum groundwater level occurs during the spring immediately after snowmelt and the minimum groundwater water level occurs during the summer due to high evapotranspiration and low precipitation. For these selected vulnerability assessment methods (modified SINTACS, the AVI and GALDIT), climate change will have impacts on the parameters that are relevant to the groundwater level (groundwater recharge, depth to water, height of groundwater above sea level and thickness of the saturated zone). Therefore, the vulnerability of groundwater under a climate change scenario was assessed based on the groundwater level data obtained from A1B (2021–2050) under mean and dry climate conditions. The other parameters (unsaturated zone material, soil media, aquifer media, K-value and slope) were assumed to be static, as under the present conditions. The vulnerability index maps under climate scenario A1B (2021–2050) were compared with the vulnerability index for the present.

4 SUMMARY OF THE ORIGINAL PUBLICATIONS

4.1 Paper I

The focus of Paper I was on the applicability of the method used to assess the impact of future climate variations and sea-level rise on groundwater recharge and the groundwater level in the shallow, unconfined, low-lying coastal Hanko aquifer in southern Finland by using groundwater flow modelling as an assessment tool. The 1D Unsaturated-Zone Flow (UZF1) package was coupled with 3D groundwater flow MODFLOW-2005 model to simulate flow from the unsaturated zone through the aquifer, using the infiltration water values produced by the snow and potential evapotranspiration (PET) models. This transient groundwater flow model provided information not only on groundwater recharge into the aquifer system, but also on surface water and groundwater interactions, such as groundwater discharge to sea water and to low-lying areas. It thus provided a more realistic picture of the groundwater recharge process than previous studies, taking into account the position of the groundwater level in each time step (Scibek & Allen 2006, Scibek et al. 2007, Jyrkama & Sykes 2007, Okkonen 2011, Jackson et al.2011, Ali et al. 2012, Assefa & Woodbury 2013, Okkonen & Kløve 2011). The A1B and B1 climate and sea-level rise (high and medium) scenarios were applied and the water balance in the model domain compared against the reference period of the present data (1971–2000). The simulations showed the impacts of changes in groundwater recharge and sea-level rise on groundwater storage and surface leakage in the Hanko aquifer. Changes in the groundwater recharge pattern from the present were predicted for 2071–2100 in both scenarios, with peak recharge not occurring during late spring but earlier, during the winter and spring. A future increase in the winter temperature could increase winter rainfall, cause more snowmelt, and reduce the snowpack, which would allow more water to infiltrate into the soil and further enhance groundwater recharge during the winter and early spring. However, a continued increase in air temperature and evapotranspiration during late spring and a reduction in precipitation would cause a reduction in groundwater recharge and pose a risk of water shortages during the summer. The simulated surface leakage showed strong correlations with groundwater recharge and the sea level. Increased groundwater recharge and sea-level rise in a future climate would raise the groundwater table and cause more surface leakage to low-lying areas, increasing the risk of flooding from surface overland flow during the winter and early spring. Moreover, a rising sea level in the future would cause some parts of the aquifer to be submerged under sea water, with the associated risk of compromising groundwater quality. The simulation results from this study provide useful information not only for the groundwater resources management, but also for land users and land-use managers to support land-use planning and management in the study area.

4.2 Paper II

Paper II clarified the origin and the factors controlling groundwater quality, the main water type and the geochemistry of groundwater in the low-lying coastline aquifer in cold, snow-dominated southern Finland. This study highlighted the importance of integration of the methods used, which consisted of a field investigation, well monitoring, multivariate statistical approaches (principal component analysis (PCA) and hierarchical cluster analysis (HCA)), the stable isotopes ^{2}H and ^{18}O, and conventional hydrogeochemical analysis. The stable isotopes ^{2}H and ^{18}O clearly suggested that the Hanko aquifer recharges directly from meteoric water (snowmelt and rainfall), with minor or insignificant contributions from the Baltic Sea and the lake above the aquifer. However, the use of stable isotopes ^{2}H and ^{18}O alone to identify seawater–aquifer interaction is not sufficient to determine the rate of water exchange and could not provide evidence of seawater intrusion into the aquifer. On the other hand, the geochemistry of groundwater suggests sulphate reduction in the mixed zone between fresh and seawater, indicating that local seawater intrusion may temporarily take place in the low-lying coastal area. This also suggested that even though the salinity of the Baltic Sea is low, the groundwater pumping wells need to be carefully positioned and the pumping rates well managed to avoid such a mixing zone. In addition, in coastal aquifers with a low hydraulic gradient, hydrogeochemistry should be used to confirm the intrusion of seawater.

An important finding was that the groundwater geochemistry of the coastal aquifer in Hanko was generally very similar to that of inland shallow aquifers in Finland. The groundwater is mainly of the Ca-HCO_3 type, with low dissolved element concentrations, as well as low pH, alkalinity, Ca and Mg concentrations due to rapid percolation or a short residence time. Being located in a cold, snow-dominated region, the geochemistry of groundwater in Hanko aquifer clearly shows spatial and temporal variations according to changes in precipitation. The concentrations of Ca and HCO_3, EC, and $KMnO_4$ consumption increased in most monitored wells with an increase in precipitation, while the concentrations of Fe, Al, Mn and SO_4 were occasionally higher soon after snowmelt. Based on the future climate scenarios, precipitation in the Hanko area is expected to increase, in addition to a rise in the Baltic Sea level. This could cause increased recharge of the aquifer from surface water and seawater intrusion due to the sea-level rise and storm surges, as well as increased groundwater abstraction. An increase in groundwater quality deterioration along the coastline can be expected in the future. The multivariate statistical approaches PCA and HCA were useful tools to extract the main components that are able to identify the vulnerable areas of the aquifer impacted by natural or human activities, either at regional or site-specific scales. The integration of PCA and HCA with conventional classification of groundwater types, as well as with the hydrogeochemical data, provided an understanding of the complex groundwater flow system to support aquifer vulnerability assessment and groundwater management in the future.

4.3 Paper III

In Paper III, groundwater intrinsic vulnerability assessments under climate change scenarios were performed for the aquifer area in Hanko, southern Finland, by utilising the results concerning climate change impacts on recharge, as well as the effects of sea-level rise on groundwater–seawater interaction, from Paper I and the results of the hydrogeochemistry study in Paper II to verify the validation of the methods. This study represented the first attempt in Finland to assess the groundwater intrinsic vulnerability of a coastal aquifer area to contamination from sources on the ground surface and seawater intrusion, and to develop a modification of the assessment method that is more suitable for shallow glaciogenic aquifers. Three intrinsic vulnerability mapping methods, a modified SINTACS, the AVI and GALDIT, were applied and compared in order to identify the most suitable method for the vulnerability assessment of the shallow, unconfined, low-lying coastal aquifer at Hanko. The vulnerability assessments were evaluated in order to verify the validation of the methods (National Research Council 1993). However, the validation of the method was not always an easy task, especially in the aquifer areas that have not been contaminated. In this study, multivariate statistical approaches (PCA and HCA) were applied to identify the vulnerable areas of the aquifer impacted by natural or human activities, and together with the hydrogeochemical data, to verify the validation of the methods.

The results demonstrated that the degree of groundwater vulnerability is greatly impacted by seasonal variations in groundwater recharge during the year, and will also vary depending on climate change variability in the long term. Groundwater is potentially highly vulnerable to contamination from sources on the ground surface during the period of high groundwater recharge after snowmelt, while high vulnerability to seawater intrusion could take place in the dry season when the groundwater recharge rate is low. The contribution of seawater to the aquifer is presently very small. The degree of seawater intrusion in the future will probably remain the same as at present. However, overpumping could induce greater seawater intrusion into the aquifer. Sea-level rise predicted under climate change scenarios will cause some areas along coastline to be below the seawater level. This, together with the coastal flooding of low-lying areas due to storm surges, could increase the contamination of the aquifer with seawater.

Paper III also highlighted the importance of the integration of groundwater vulnerability assessment methods for the shallow, unconfined, low-lying coastal aquifers. The results from the GALDIT method provided greater insights into groundwater vulnerability to seawater intrusion in coastal aquifers, particularly in areas having a low hydraulic gradient, which cannot be identified by the AVI or modified SINTACS. Groundwater intrinsic vulnerability index maps calculated from the AVI were similar to the results of the modified SINTACS; however, the AVI does not take into account the impact of sea-level rise, unlike the modified SINTACS. The AVI is probably not suitable for groundwater vulnerability assessment of coastal aquifers or aquifers that have been strongly impacted by climate change. The modified SINTACS could be used as a guideline for the groundwater vulnerability assessment of glacial and deglacial deposits in inland aquifers, such as in Finland as a whole. In addition, a combination of the modified SINTACS and GALDIT could provide a useful tool for assessing groundwater vulnerability to both contamination from sources on the ground surface and to seawater intrusion for shallow, unconfined, low-lying coastal aquifers under the present and future climate change conditions.

5 DISCUSSION

5.1 Origin of groundwater and groundwater and surface water interaction (II)

The stable isotopes ^{18}O and ^{2}H are commonly used to identify the origin of water as well as the interactions of groundwater and surface water (Gonfiantini 1986, Richter & Kreitler 1993, Taylor & Howard 1996, Clark & Fritz 1997, Kendall & McDonnell 1998, Allen 2004, Faure & Mensing 2005). The ^{2}H and ^{18}O values in groundwater from the Hanko aquifer were consistent with the results of Kortelainen and Karhu (2004) and Kortelainen (2007), who reported mean ^{2}H and ^{18}O values of groundwater from southern Finland of -82.0 ± 0.9‰ and -11.55 ± 0.14‰ VSMOW, respectively. The stable isotopes ^{2}H and ^{18}O in the groundwater of Hanko are also consistent with the mean ^{2}H and ^{18}O values in precipitation from southern Finland, which are -82.0 ± 23.6‰ and -11.54 ± 3.1‰ VSMOW, respectively. These values are distinct from those of surface water, as the mean ^{2}H and ^{18}O values of lake water are -55.57 ± 9.6‰ and -6.85 ± 2.1‰, respectively, and the respective means of seawater are -57.65 ± 2.4‰ and -7.55 ± 0.4 ‰.

Most of the ^{2}H and ^{18}O values of groundwater from Hanko fall closely on the Finnish local meteoric water line (LMWL) (Fig. 5 in Paper II), indicating direct recharge from precipitation (snowmelt and rainfall) with no indication of evaporation or a contribution from the surface water. The majority of the groundwater samples showed narrow temporal and spatial variation with low standard deviations of 1.6‰ and 0.23‰ for ^{2}H and ^{18}O, respectively (Fig. 5 in Paper II). The narrow variations of most of the data may indicate the same source of groundwater recharge, with a short percolation time. The fluctuation in the groundwater levels in many observation wells (Fig. 3 in Paper II) indicates a rapid response of the groundwater level to precipitation during the snowmelt period and heavy rainfall events, which reflects the short percolation time. This is consistent with many wells that contain quite a thin vadose zone and/or the high hydraulic conductivity of aquifer materials. However, the observation wells next to a gravel excavation pit and the lake shoreline showed high seasonal variation with high standard deviations of 3.21‰ and 0.49‰ for ^{2}H and ^{18}O, respectively. This high variation may indicate a short percolation time and the influence of surface water from the gravel excavation pit and lake water.

The median concentrations of major ions in the groundwater were low and close to the median concentrations of precipitation (Vuorenmaa et al. 1999, Järvinen & Vänni 1996, 1997), being lower than the median values of shallow groundwater in Finland (Lahermo et al. 2002). The concentrations of minor ions and trace elements (F, Fe, Ag, Be, Bi, Br, Cd, Co, Cr, P, PO_4, Se, Th and Tl) in many wells were below or close to the detection limit. However, the median values of metals and trace elements such as Fe, As, Cd, Cr, Ni, Pb, Sb, Se, I, Li and PO_4 from groundwater samples were higher than those reported by Lahermo et al. (2002) (Table 2 in Paper II).

The composition of groundwater in Hanko is mainly of the Ca-HCO_3 type. Only the samples from the upper part of a well located next to the highway had a composition of groundwater closer to the Na-Cl type. The Ca-HCO_3 type of groundwater, with low dissolved ion concentrations, low pH, alkalinity, Ca and Mg, is common for glaciated areas in Finland (e.g. Backman et al. 1999, Soveri et al. 2001, Korkka-Niemi 2001, Lahermo et al. 2002, Backman 2004). This is consistent with the finding of low dissolved concentrations of elements in many groundwater samples. Elevated concentrations of Na and Cl in wells in a downstream direction from the highway indicate the influence of de-icing chemicals (NaCl). The use of salt for de-icing purposes in Finland increased in 1987, with a peak in 1990, when 157 000 tons of salt was applied along the highways in southern Finland. Many of these run on top of the First Salpausselkä formation, including the Hanko area. There have been attempts to reduce the use of de-icing road salt since 1993 (Gustafsson & Nystén 2000).

No intrusion of seawater was observed in the observation wells that are located next to the coastline or in the water intake well. The chloride concentration of seawater in this study was 2 690 mg l^{-1}, which is consistent with other studies, e.g. Alenius et al. (1998) and Fagerlund (2008). The Cl contribution to the groundwater calculated from the Cl concentrations of water samples, seawater and fresh water (Appelo & Postma 2005), was less than 0.5%, which was very low and could have had another origin than direct seawater intrusion, e.g. atmospheric fallout (Korkka-Niemi 2001). However, according to the Piper diagram, sulphate reduction may possibly be observed in the observation wells Obs10 and Obs11 that are located in a low-lying area near the coastline and in the water intake well (Fig. 3). Based on the geochemistry of three water samples from this well, SO_4 showed a strong negative correlation with HCO_3 (r = 0.98, < 0.01). Seawater has a high SO_4 concentration, and when it intrudes into an aquifer, especially into an anoxic low-lying coastal aquifer, it may result in sulphate reduction (Andersen 2001, Appelo & Postma 2005) and have a negative correlation with HCO_3. However, the reduction of sulphate combined with the enrichment of bicarbonate in the mixing zone suggests bacterial reactions (Magaritz & Luzier 1985). The monitoring data indicate that the groundwater level is occasionally lower than the seawater level, either due to overpumping or sea-level rise, which could temporarily cause seawater intrusion into the aquifer.

5.2 Impacts of climate change on groundwater recharge (I, III)

Under the changing climate (IPCC 2007), a potential increase in precipitation in the winter, spring and autumn and increased evapotranspiration in summer owing to rising temperatures is expected and has been reported in many northern latitude study areas (e.g. Scibek & Allen 2006, Scibek et al. 2007, Jyrkama & Sykes 2007, Okkonen & Kløve 2011,Okkonen 2011). In the shallow low-lying Hanko aquifer in southern Finland, changes in the groundwater recharge pattern from the present were predicted in the A1B (2071–2100) and B1 (2071–2100) scenarios, with peak recharge not occurring during late spring but earlier, during the winter and spring. A future increase in winter temperatures could increase winter rainfall, cause more snowmelt and reduce the snowpack, which would allow more water to infiltrate into the soil and further enhance groundwater recharge during the winter and early spring. However, a continued increase in air temperature and evapotranspiration during late spring and a reduction in precipitation would cause a reduction in groundwater recharge and pose a risk of water shortages during the summer.

The changes in the groundwater recharge pattern, with high seasonal variations under the future climate change scenarios, are consistent with studies on a shallow inland aquifer (Okkonen 2011). However, in the Hanko aquifer, which is located in an area with a relatively low elevation, this would cause the aquifer to become more vulnerable to climate change than the inland aquifer. The simulated surface leakage showed strong correlations with groundwater recharge and the sea level ($r = 0.90$, < 0.01). Increased groundwater recharge and sea-level rise in a future climate would increase the groundwater levels and cause more surface leakage to low-lying areas, increasing the risk of flooding from surface overland flow during the winter and early spring. Moreover, a rising sea level in the future would cause some parts of the aquifer to be submerged under seawater, with the associated risk of compromising groundwater quality. Therefore, the impacts of climate change would potentially affect not only the groundwater, but also the surface water. For sustainable groundwater resource management and land-use planning, it is important to understand the hydrogeological processes and the interactions between groundwater and surface water, and the factors affecting groundwater quality.

5.3 Impacts of climate change on groundwater quality (II)

Seasonal variations in groundwater quality are typical in northern regions and have been reported in many unconfined shallow aquifers in Finland. For example, a lower dissolved concentration of elements in groundwater during the snowmelt period indicates the effects of snowmelt (Backman et al. 1999, Korkka-Niemi, 2001, Okkonen, 2012). Similarly to the Hanko aquifer, groundwater samples have revealed spatial and temporal variations in dissolved solute concentrations. Overall, the concentrations of Ca, HCO_3, EC and $KMnO_4$ consumption increased in most wells with an increase in precipitation. An increase in $KMnO_4$ consumption implies the influence of surface water or dissolved organic matter (Korkka-Niemi 2001, Lahermo et al. 2002).

The concentrations of Fe, Al, Mn and SO_4 were occasionally high during the spring, immediately after the snowmelt period. However, their concentrations were highly variable and often associated with low pH values. Iron, Mn and SO_4 are redox-sensitive elements in groundwater and are soluble under reducing conditions (Hem 1985, Shand & Edmunds 2008). High concentrations of Al can be associated with clay minerals or organic matter, and Al had a high positive correlation with $KMnO_4$ consumption, with a Pearson correlation coefficient of 0.79 (< 0.01).

A continuous increase in NO_3 and metal concentrations in groundwater following an increase in precipitation was observed in wells that are located in the downstream area. Although these concentrations are still low compared with the drinking water standard (WHO 2011), the continued increase in NO_3 and metal concentrations in groundwater indicates a potential contamination risk to the aquifer. Okkonen and Kløve (2011) and Korkka-Niemi (2001) reported a decrease in the concentration of NO_3 in groundwater during the spring, when recharge from snowmelt occurs. In contrast, high NO_3 concentrations in spring and autumn were found due to increased nitrogen leaching associated with the increase in runoff from forest (Lepistö 1996) and drained peatlands (Kløve 2001).

For wells that are located along the coastline and close to a water intake well, the groundwater samples contain higher EC and dissolved ion concentrations than inland wells, and EC, Ca, HCO_3 and $KMnO_4$ consumption have been observed to increase during the spring after snowmelt, while the Cl concentration has decreased. A decrease in the Cl concentration during the snowmelt period in spring with a high hydraulic gradient may indicate the discharge of groundwater into the sea.

Based on the future climate scenarios A1B and B1, by the end of 2100, precipitation in the Hanko area is expected to increase by 12–26% compared with the current situation and the sea level will rise by up to 0.51 m above the current mean sea level. The potential increase in precipitation during the autumn and winter in the future could cause more freshwater to enter the aquifer and possibly a greater influence of seawater intrusion due to the sea-level rise and storm surges. Based on the observed seasonal variation, an increase in the concentrations of some dissolved elements, as mentioned earlier, and changes in the groundwater geochemistry of wells along the coastline can be expected.

5.4 Impacts of climate change on groundwater vulnerability (I, II, II)

The shallow permeable aquifer at Hanko is located in a cold, snow-dominated region where the groundwater level clearly displays seasonal variations. The maximum groundwater level occurs during the spring after snowmelt and in the autumn due to the lower evapotranspiration rate. The minimum groundwater level occurs during the winter due to the lack of percolation resulting from the snow cover and during the summer due to the higher evapotranspiration rate. Under the climate change scenarios, the seasonal impacts of climate change and climate variability on groundwater recharge and the groundwater level will be more significant (Okkonen 2011, Mäkinen et al. 2008). These will consequently affect the vulnerability of groundwater to contamination in different seasons during a year.

Based on climate change scenarios, increasing precipitation can cause an increasing frequency of heavy rainfall events, which are associated with flash floods and the intrusion of surface waters into aquifers. Surface water may contain bacteria, a high amount of organic carbon and other dissolved solids, which will cause a deterioration in groundwater quality (Tarvainen et al. 2013). High concentrations of $KMnO_4$ consumption were detected in the observation wells located next to the lake and low-lying aquifer areas in Hanko, which indicated surface water intrusion into the groundwater. Increasing temperatures will cause snowmelt to occur earlier in the year and will affect the distribution of surface runoff and lead to increasing groundwater recharge in winter. Increasing groundwater recharge will in turn lead in a rise in the groundwater level and an increase in surface leakage, which may cause flooding in the aquifer area. This could also increase aquifer vulnerability by enhancing the transport of surface and soil contamination into the aquifer. Following an increase in groundwater recharge, such as in spring, the groundwater vulnerability index of contamination on the ground surface from the modified SINTACS and the AVI will also increase, while GALDIT will show the opposite result.

On the other hand, with a decrease in groundwater recharge, such as in the summer, the index of groundwater vulnerability to contamination from the ground surface based on the modified SINTACS and the AVI will decrease, while the index of vulnerability to seawater intrusion based on GALDIT will increase. Because decreasing groundwater recharge will lower the groundwater level relative to the seawater level, there will be a decline in the hydraulic gradient and groundwater flow velocity, and this could reduce groundwater flux discharge to the sea and induce greater seawater intrusion into the aquifer.

In the Hanko area, sea-level changes have a direct effect on shallow groundwater tables after a short time lag (Backman et al. 2007). Seawater intrusion may occur continuously and the degree of intrusion depends on the seawater and fresh water interface mechanisms and many factors associated with natural and anthropogenic sources. Although the present contribution of seawater to the aquifer was found to be less than 0.3%, the hydrogeochemical data from water samples taken during this thesis study indicate the possibility of temporal seawater intrusion into the low-lying coastal area. Ferguson and Gleeson (2012) reported that groundwater abstraction could cause a greater increase in the vulnerability to seawater intrusion for a low-lying coastal aquifer than sea-level rise. In the Hanko area, overpumping due to the seasonal increase in the groundwater demand during the summer, for example from the increased number of tourists and/or the owners of summer cottages (Luoma et al. 2013), could lower the groundwater level, especially in the water intake area, and may cause the aquifer to become more vulnerable to seawater intrusion. Under drought conditions, this could lead to a potential water shortage during the summer.

In addition, the coastal flooding of the low-lying area due to storm surges could transport potential contaminants from seawater into the aquifer. The highest storm surge experienced by the Hanko aquifer area stands at 1.24 m a.s.l., which occurred on 9 January 2005 and caused parts of the low-lying aquifer area to be submerged under seawater. Based on climate change scenarios A1B and sea-level rise A1B (high regionalised), the mean sea level is predicted to reach +0.51 m a.s.l. and the potential storm surges could reach 1.75 m a.s.l. by the end of the 21st century. At this level, the areas below +0.51 m a.s.l. would be submerged under seawater, and the areas below 1.75 m a.s.l., including the water intake well, would be vulnerable to coastal flooding.

By the end of 21st century, the density and salinity of the Baltic Sea water are predicted to be the same as or lower than at present due to the increasing input of fresh water into the Baltic Sea (Meier et al. 2006). The degree of seawater intrusion is therefore probably not a major concern compared with coastal flooding of the aquifer due to sea-level rise and storm surges.

Based on the main findings in this study, the degree of groundwater vulnerability to contamination and seawater intrusion of the Hanko aquifer greatly depends on climate change variability in the long term and could also vary following the seasonal variations during the year in either high or low groundwater recharge. This will challenge the management of the water supply and the strategy applied for the coastal aquifer in Hanko, including optimisation between groundwater abstraction and the intrusion rate of seawater for the water intake wells during the peak season in summer, the possibility of establishing a new water intake well further inland owing to the threats of future sea-level rise and storm surges, and the protection of groundwater to maintain water quality that meets the drinking water standards and prevents it from contamination.

6 CONCLUSIONS

This thesis study clarified that the groundwater vulnerability of a shallow permeable aquifer located in the cold snow-dominated brackish coastal area in southern Finland is greatly impacted by seasonal variations in groundwater recharge during the year, and will also vary depending on the climate change variability in the long term. The potential for high groundwater vulnerability to contamination from sources on the ground surface occurs during the high groundwater recharge period after snowmelt, while high vulnerability to seawater intrusion could take place during the low groundwater recharge period in the dry season. The seasonal variations in groundwater recharge correspond directly to the spatial and temporal variations in the geochemistry of groundwater in the aquifer area.

The estimation of groundwater recharge and surface leakage, as well as the groundwater vulnerability assessment of the shallow, unconfined, low-lying Hanko aquifer located in the cold snow-dominated brackish coastal area of southern Finland under the future climate change and sea-level rise scenarios required an integration of multiple approaches, as highlighted in this thesis:

1. The coupling of the Unsaturated-Zone Flow (UZF1) model package with the three-dimensional groundwater flow MODFLOW model to simulate flow from the unsaturated zone through the aquifer provided a continuous groundwater flow from the ground surface through the groundwater table, which is needed for the simulation and prediction of the potential impacts of climate change on groundwater recharge under the future climate and sea-level rise scenarios. The data received from this simulation consisted of information on the flow in both unsaturated and saturated zones, and also the surface leakage, which provides useful information not only for groundwater resource management but also for land-use planning in the area.

2. Monitoring data are needed for the long-term study of groundwater conditions under climate change and variability. Shallow, unconfined aquifers rapidly respond to seasonal variations during the year and also to climate variability in the long term. Monitoring of the groundwater level also provides the data needed for model calibration.

3. The stable isotopes ^{2}H and ^{18}O were used to determine the origin of groundwater and the interaction of groundwater and surface water. The stable isotopes ^{2}H and ^{18}O clearly suggest that the shallow low-lying coastal aquifer in Hanko recharges directly from meteoric water (snowmelt and rainfall), with minor or insignificant contributions from the Baltic Sea and the lake above the aquifer.

4. The integration of the multivariate statistical approaches, PCA and HCA, with the conventional classification of groundwater types using the Piper diagram, as well as with the hydrogeochemical data, can be used to identify the vulnerable areas of the aquifer impacted by natural or human activities and provide an understanding of the complex groundwater flow systems to support aquifer vulnerability assessment and groundwater management in the future. The hydrogeochemical data can be used to validate the current situation of the vulnerable aquifer area.

5. A combination of groundwater vulnerability assessment methods is needed for shallow, unconfined, low-lying coastal aquifers. Based on the comparison results of the three selected intrinsic vulnerability mapping methods (modified SINTACS, the AVI and GALDIT), the results from GALDIT provide a better insight into groundwater vulnerability to seawater intrusion of the coastal aquifer, particularly in areas having a low hydraulic gradient, which cannot be identified by the AVI or modified SINTACS. The AVI provides a simpler and quicker assessment of aquifer vulnerability to contamination from the ground surface, but it does not take into account the impact of sea-level rise, unlike the modified SINTACS. The AVI is probably not suitable for groundwater vulnerability assessment of coastal aquifers or of aquifers that are likely to be strongly impacted by climate change. The modified SINTACS could be used as a guideline for the groundwater vulnerability assessment of inland aquifers formed in glacial and deglacial deposits. Furthermore, a combination of the modified SINTACS and GALDIT could provide a useful tool to assess the vulnerability of groundwater to both contamination from sources on the ground surface and seawater intrusion for shallow, unconfined, low-lying coastal aquifers under future climate change conditions.

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ORIGINAL PUBLICATIONS

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II Luoma, S., Okkonen, J., Korkka-Niemi, K., Hendriksson, N. & Backman, B. 2015. Confronting the vicinity of the surface water and sea shore in a shallow glaciogenic aquifer in southern Finland. Hydrol. Earth Syst. Sci. 19, 1353–1370, doi:10.5194/hess-19-1353-2015. Available at: http://www.hydrol-earth-syst-sci.net/19/1353/2015/

III Luoma, S., Okkonen, J. & Korkka-Niemi, K. 2016. Comparison of the AVI, modified SINTACS and GALDIT vulnerability methods under future climate-change scenarios for a shallow low-lying coastal aquifer in southern Finland. Hydrogeology J., doi:10.1007/s10040-016-1471-2. Available at: http://link.springer.com/article/10.1007/s10040-016-1471-2

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The potential impacts of climate change (due to change in precipitation and temperature) on groundwater resources of shallow, unconfined, low-lying coastal aquifers could cause risks not only from the change in recharge patterns but also from sea-level rise, making coastal aquifers more vulnerable to this change than those inland. In addition, the risks from human activities in the aquifer areas emphasize groundwater vulnerability. Because the aquifer investigated in this thesis study is located in a cold snow-dominated region, the seasonal variation in groundwater recharge will be strongly affected by climate change in terms of timing and amount of groundwater recharge, which will affect the level and quality of groundwater. This doctoral thesis comprises a synopsis and three original papers with the overall aim to investigate and assess the vulnerability of groundwater to contamination in a shallow, unconfined, low-lying coastal glaciogenic aquifer in southern Finland under present conditions as well as future climate change and variability.

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